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Design, Manufacture and Testing of Structural Trusses Using Additively Manufactured Polymer Composites

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Abstract

The MIT HAUS group is exploring the use of large scale additive manufacturing (LSAM) to mass produce low-cost structures using recycled polymer composites. This study demonstrates the ability to design and produce efficient truss elements and assemble these elements into a floor system with the truss as the central element. The truss was designed to maximize the stiffness-to-weight ratio while being efficiently producible using LSAM. This design process entailed both finite element simulations and small-scale testing of additively manufactured trusses. Based on this, a truss design was selected for full scale production and testing. This design spans 8 ft, and is 13 in. high and has a thickness of 1 in. Using an rPET-GF30 composite material, a series of trusses were produced on a Cincinnati BAAM 603. Each truss was produced in 13 minutes and weighed 13 lbs. Trusses were then tested individually to measure the midpoint deflection and to provide calibration of the FEA. This process achieved a model - data error of less than 10 %.

Using a series of 4 trusses a 4 ft x 8 ft floor system was built that, with the exception of the plywood top, is entirely produced via additively manufactured components using the rPET-glass fiber composite material. The resulting structure was tested to compare load-deflection values with typical construction standards. This comprised loading the floor with bags of sand, to simulate a distributed load, and measurement of the maximum deflection point in the center of the middle trusses. This testing revealed that the floor was well within the International Code Council's (ICC) deflection standards, and demonstrated an overall center point stiffness of 3,825 lb/in. A finite element simulation of the complete structure was created and found to predict this same stiffness to within 10% of the measured value.

Finally, the FEA simulation was explored to identify the maximum stiffness-to-weight ratio for this truss design using truss depth as the design variable. It was found that the maximum stiffness-to-weight ratio is achieved at a truss height of 16.3 in.

Keywords: Large Scale Additive Manufacturing (LSAM), Structural Design for LSAM, Structural Testing, Trusses, Polymer Composites

Introduction

The MIT HAUS project has the goal of producing homes using large scale polymer composite additive manufacturing with recycled polymers. Ambitiously, the group seeks to provide a solution to the global housing problem, where the United Nations Human Shelters Program estimated that there are between 1.6 and 3 billion people in the world without decent housing [1]. This need requires homes to be produced globally in great volume using minimal resources and at very low cost. One untapped source of material is the large quantity of un-recycled polymers, with global production doubling between 2000 and 2019 to 460 million tons and it is expected to keep rising according to an OCED report [2]. This project has focused on using recycled Polyethylene Terephthalate (rPET) owing to its abundance and good structural properties, especially when infused with glass fibers.

The amount of waste from single use PET bottles and packaging is an opportunity to create greatly increased demand for recycled PET and provide low cost homes at the same time. Combining low cost recycling with large scale additive manufacturing (LSAM) can provide solutions to both the plastic waste and housing problems. The size of both problems leads to the need for high production rates, which for LSAM means that parts need to have simple tool paths and be lightweight, since weight directly affects production time and cost. When production aims to be on the scale of hundreds of millions of units, small weight and time savings become vital, as shaving just 1 second off a print time for 1 part is a 3 years savings in total production time with 100 million parts to be produced. While minimizing weight and production time is important, it is also important to maintain structural performance to ensure that the homes created meet building codes.

LSAM is not without constraints that limit what can be produced. To that end a modular approach has been taken to designing and eventual production of a home. For example, Perez et al. have developed foundations [3] and Perez et al. developed pile footings [4]. Building on the foundation example, we considered a LSAM produced floor system. The most critical element of a floor system is the joist to span the floor and provide bending stiffness. This work presents the design and testing of LSAM produced trusses made from a recycled polymer composite demonstrated in a floor system. Therefore in this work our measure of performance is the stiffness-to-weight ratio (k/w) for the floor system.

Background

Truss Design

Trusses are used for many applications, including floor and roof joists. Wooden trusses are commercially available and retailers such as Menard's [5] have guides for choosing trusses. Menard's also states that floor trusses need to be custom made, instead of the stock shapes for I-beams and dimensional lumber [5]. The trusses also provide advantages over solid joists such as longer spans needing fewer support beams, easier and quicker installation, and easily placed piping, HVAC, and electrical work leading to reduced cost of the floor system [5].

Floor trusses are primarily made from wood which manufacturers assemble from precut wood connected together at nodes by metal plates with spikes in it that dig into the wood when pressed together [6]. Here we use LSAM to produce the truss in one print with no assembly required as the truss members are bonded together at nodes where the hot polymer flows together during the printing process creating a bond. In addition LSAM allows for greater flexibility than wooden trusses since a simple program change is all that is required to change the truss design. Flexibility in the tool path provided by additive manufacturing and advancements in topology optimization may lead to the complex results from the optimization being able to be produced additively [7,8]. In this work the design process began with standard truss designs that were known to be both manufacturable and acceptable to the construction industry. This process is laid out further below.

Floor Systems

Traditional construction in the United States consists of light wood framing, first employed in the mid-1800s [9]. Floor systems consist of joists, girders, and sheathing [9]. Joists span horizontally, girders hold the joists, and sheathing goes on top of the joists. Joists are typically 2x6 up to 2x12 and sheathing is typically ⅝ in or ¾ in thick 4 ft x 8 ft panels of plywood [9]. Wooden I-beams and trusses are also used [9]. In this study the goal is to substitute LSAM produced trusses for typical wood joists, and explore the limits of production speed and material cost.

The performance of a floor structure is typically determined by maximum deflection limits using typical loading conditions for a house. Floor standards have been developed by the ICC in their International Building Code (IBC) [10] based on guidelines from the US Department of Housing and Urban Development [9]. HUD's Design Loads for Residential Construction document lays out the loading conditions for residential structures. For floors, the dead load of the structure and the live loads of use of the floor are the types of loads to be concerned with [9]. The HUD Residential Structural Design Guide [9] lays out the typical dead and live loads in its document and presented as replicates here in Tables 1 and 2.

Floor Type	**Load (psf)**
Wood Flooring	12
Ceramic Tile	15
Slate	19

Table 1: HUD Design Dead Loads for Floor Construction. The table is a replica of Table 3.2 in HUD's "Design Loads for Residential Buildings" [9].

Floor	**Uniform Load (psf)**	**Concentrated Load (lbs)**
Bedroom	30	300
Other	40	300
Garage	50	2000 (SUV)

Table 2: HUD Design Live Loads for Floor Construction. The table is a replica of Table 3.4 in HUD's "Design Loads for Residential Buildings" [9].

The concentrated load should be applied to an area that makes sense for the load applied, i.e. the weight of a person walking up the stairs is to be applied in the middle of the stair with an area of a person's foot [9]. This area will change based on what the concentrated load is as a person and a storage box have different areas. Given these loadings, the IBC standard for maximum floor deflection is L/360 [10], where L is the length of the span, where the maximum is typically in the midpoint of the span [10].

3D Printed Homes

There are companies that currently produce 3D printed home structures. In a review of 3D printed structures by Garcia-Alverado et al. [11], most had printed walls either on-site or off site, with some having roofs and walls printed and very few with foundations printed and most were made from concrete or clay materials. Concrete 3D homes are limited to walls, and need other methods to produce floors and roofs. It should be acknowledged that there are companies like Azure that make customizable 3D printed homes (typically ADU's) out of recycled polymers [12].

Stiffness-to-Weight Ratio

Stiffness-to weight ratio (herein referred to as k/w) is a measure that can be used to evaluate the performance of a truss design. This should not be confused with specific stiffness (E/ϱ) which is an intrinsic material property. In the general case, this measure can be changed by modifying both the material and geometry. In the most general case, for example, Baskin and others [13] have developed a framework for design choices for lightweighting structures, with material and stress as inputs. In this work we hold the material fixed and focus on maximizing k/w by manipulating the truss geometry taking advantage of the inherent flexibility in LSAM. In the following the truss design choices will be based on maximizing k/w given practical constraints imposed by additive manufacturing.

LSAM (Large Scale Additive Manufacturing)

LSAM typically involves a pellet-based screw extrusion system with the extruder mounted on a gantry or a robotic arm with sizes for gantry systems ranging from the smaller BAAM 603 with a print bed of 6 ft x 12 ft [14] to the Thermwood 1540 with a print bed of 15 ft x 40 ft [15]. Other manufactures include CEAD [16] and Ingersoll Machine Tools that make both gantry and robotic LSAM machines, with the Ingersoll MasterPrint 3x having a print bed of roughly 12 ft x 20 ft [17]. LSAM machines have been typically used to create prototypes or molds for industries such as defense, aerospace, and marine, but the machines are capable of mass production.

All large scale parts printed for this work were made using a Cincinnati BAAM 603 in the HAUS lab at MIT. While the extruder can run at a maximum of 80 lb/hr [14] for these experiments our BAAM was kept at 50 lb/hr while the Thermwood 1540 that can run at 500 lb/hr [15] and the MasterPrint 3x capable of up to 1000 lb/hr [17]. Nozzle size, screw size, and various details regarding feeding on the extruders vary. The HAUS group extruder uses an anti-clog tapper with a gravity feed from the hopper to the barrel and a cold jet is also pointed at the feed tube to prevent uneven pellet feeding. For all trusses considered here, a 0.4 in nozzle was used and no post-extrusion tamping was done.

Materials

Polymer-based LSAM typically uses composites, commonly glass or carbon fibers, to enhance thermal properties for printing and for better mechanical properties [18,19]. Common polymer matrices include ABS and PLA. All of the trusses detailed here were printed with

Airtech DALTHRAM-100GF, a recycled copolyester with glass fiber reinforcement of 30%. The properties of this material are given by Airtech based on specimens created using LSAM as shown in Table 3 [20].

Property	Direction	Value (GPa)
Tensile Modulus	Longitudinal to printing direction	6.6
Tensile Modulus	Transverse to printing direction	3.7
Tensile Strength	Longitudinal	79.3
Tensile Strength	Transverse	25.9

Table 3: Key Mechanical Properties of DHALTRAM T-100 [20].

The trusses presented here are 2D shapes extruded to provide the required thickness. The goal is to produce structures that maximize k/w and minimize production time. Flexibility comes from the additive manufacturing process that lends itself well to producing custom trusses that are designed for a specific job. The production rate is limited by two factors: the maximum throughput of the extruder and the layer times necessary to get good bonding while preventing layer slumping. Work done by Compton et al [21] concluded that the temperature of the previous layer must be above the glass transition temperatures to avoid warping and cracking [21]. This sets the upper limit on layer time. The lower limit is set such that the part has cooled enough to maintain its shape and resist deformation when the next layer is applied [22]. This slumping behavior is not studied to the extent of warping and cracking, but is of importance as the production time for these 2D parts is pushed to be as fast as possible.

Truss Design and Simulation

The design space explored was limited based on manufacturability on the MIT BAAM machine. BAAM machines take G-Code generated by the Oak Ridge National Laboratory's Slicer and this slicer works best with objects that have closed loop contours. These contours minimize start and stop defects caused by transient flow in the extruder and minimize non-printing production time. These constraints led to adopting a traditional truss design that is a well proven geometry that is easily produced on the BAAM.

The truss design process follows the process laid out in Perez et al. [23] where designs are proposed, tested and simulated at the small scale, and then taken to the large scale for production. Four designs were proposed, each with the same overall length of 96 in and height of 13 in. The element cross section is 0.5 in wide by 1 in deep. They are distinguished by different chord designs and by the number of web elements or nodes, shown in Figure 1.

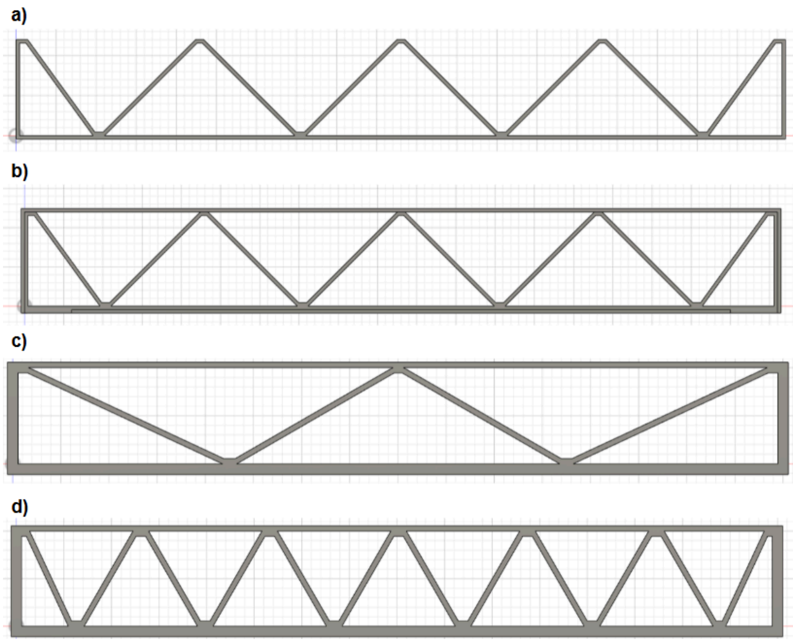

Figure 1: Truss Designs.
a) Design 1, which is a single bead print.
b) Design 2, a double bead print with 5 nodes across the top.
c) Design 3, a double bead print with 3 nodes across the top.
d) Design 4, a double bead print with 7 nodes across the top.

Note that the first design, while having no upper chord, is an example of the limitation of printing a single continuous bead. The other three designs start with a similar contour, but add a second rectangular bead around the entire perimeter. This leads to a single bead upper chord and the double bead lower chord.

Other designs were considered but were dismissed based on simulation results or the inability to slice the design in the ORNL slicer. The designs were both simulated using Fusion360 and produced on the small scale via FDM printing on an Ultimaker S5 for rapid testing assuming a full scale truss thickness of 1 in. Simulations were done for both small and large scale and the designs were sliced in the ORNL slicer to get an estimate of print times. A single layer using a 0.4 in nozzle, the time and weight for a single layer were determined as shown in Table 4 below.

Truss	Single Layer Weight (lbs)	Single Layer Print Time (s)
1	0.42	64
2	0.79	110
3	0.75	102
4	0.86	120

Table 4: Single layer print time for the different truss designs.

Finite Element Simulation of Truss Design

A simulation of the truss in 3 point bending was performed in Fusion360. The initial use of the simulation was to determine which design should be moved forward at the large scale with a comparison of relative k/w ratios. For the simulation the truss is constrained on the bottom edges, with a small platform in the center to apply a point load. The top measurement point was used for k/w comparison amongst the different designs, while the bottom measurement point was used for the experiments. A typical simulation set up is shown here in Figure 2.

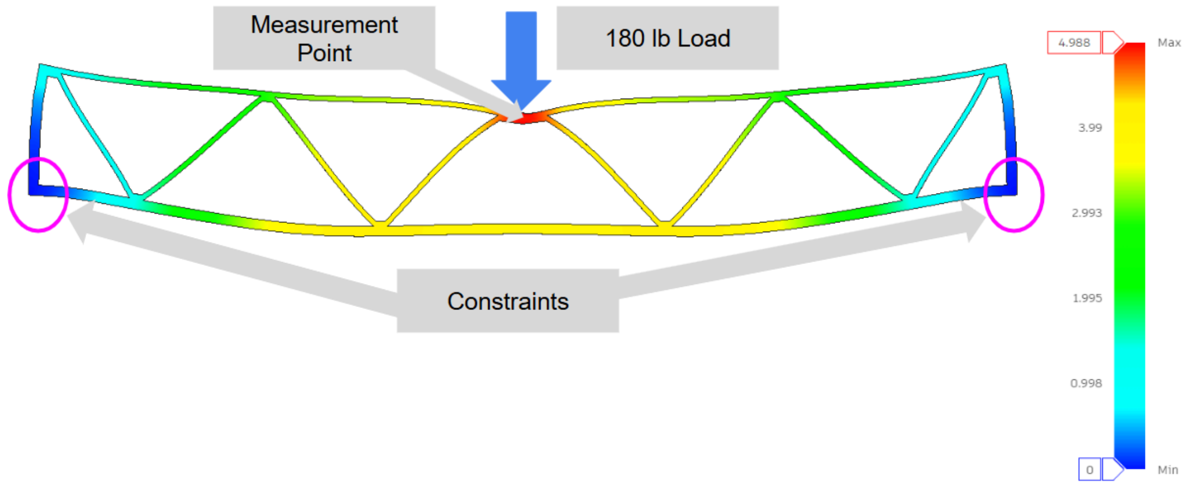

Figure 2: Truss Simulation for 180 lb. Central Load.

Since design 1 was for demonstration purposes, only the designs with the outer rectangle were compared to advance to the large scale with k/w ratios shown in Table 5:

Truss Design	Top Deflection (in)	Stiffness (lbf/in)	Truss Weight (lb)	k/w (lbf/(lb*in))
2	0.16	1,130	12.96	87
3	0.23	775	12.19	64
4	0.19	938	14.04	67

Table 5: k/w ratios of the Truss Designs. The simulation with 180 lb load.

The highest k/w is achieved with Truss 2, so that is one that was studied at the large scale.

Truss Manufacturing

The following provides some details of the actual manufacture of the trusses, which includes both ideal processing conditions and some structural details arising from manufacturing constraints.

Process Parameters

The material is dried for 1 hour at 65℃ before extruding begins for the day. The temperatures of the 7 heaters along the barrel of the extruder were set in accordance to recommendations from Airtech [20] while the extruder speed and feed rate were settled upon during printing and are shown in Table 6.

Part of Print	Extruder Speed (RPM)	Feed Rate (in/s)
Normal	350	3.31
Start Up	350	0.12

Table 6: Extruder Speed and Feed Rate for normal conditions and start up of a distance of 0.1 in.

Each truss has a length of 92 in, a height of 13 in, and thickness of 1 in; the 92 in in length was done to comfortably fit the truss on a 8 ft long board of homasote, which was used as the build plate. The start up part of the print is included to ensure that there is good quality at the beginning of the print, without it the extruder takes time to push material out, leaving a gap or area of poor quality. The parameters shown in Table 6 led to each truss being produced in 13 minutes 30 seconds, weighing 13 lbs, for a material deposition rate of ~ 60 lb/hr. The layer return time for each truss is roughly 2 minutes and 40 seconds, which is long enough to not require a dwell period to ensure that the previous layer is stiff enough to hold the load of the layer being deposited. There was also no cracking or warping observed with the trusses. An image of the truss printing in progress is shown in Figure 3.

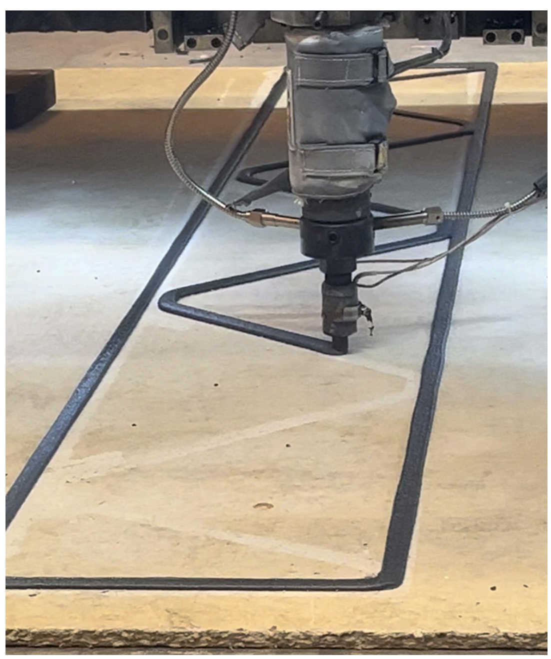

Figure 3: Printing in Progress.

Early truss prints highlighted a weak point at the nodes on the trusses. To address this, the notched joint shown in Figure 4, was developed. With this change node failure has not been observed in subsequent testing.

Figure 4: Notched Joint. Greater area for welding of beads together. In this joint, there is the potential for stress concentrations with the holes.

Tool Path Slicing

The G-Code was sliced using the Oak Ridge National Lab's Slicer 1. Figure 5 below shows the tool path.

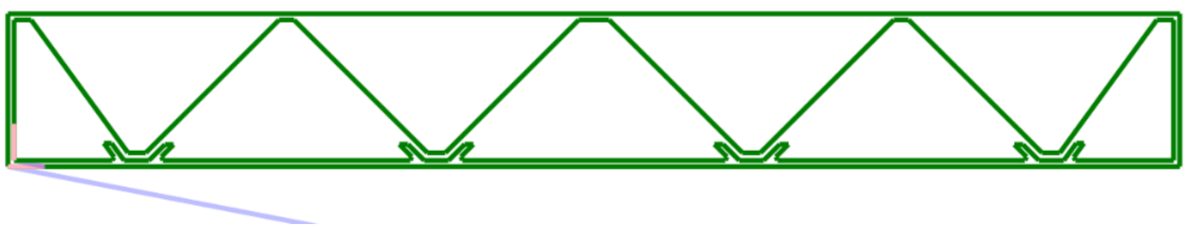

Figure 5: Tool Path. The green lines are the path the extruder follows. The pink lines represent a forward tip wipe at the end of the bead. The blue line is travel.

The code begins with a brief purge to remove material that potentially has been sitting in the barrel for a while. From then the extruder performs a start up procedure, slowing the feed rate down to allow material to extrude from the nozzle to not leave a gap of less material in the part and quickly after the feed rate goes to full speed. At the end of each bead there is a tip wipe to prevent the extruder from pulling the bead up as it moves to the next bead. The notched truss design shown is a 2 bead per layer print, with each layer taking 2 minutes and 40 seconds, for an overall print time of 13 minutes and 30 seconds, including the initial purge.

<u>Testing and Simulation of a Truss</u>

Truss Testing

A three point bending test was performed on two of the initial large scale trusses. The trusses are nominally 1 in thick. The truss was simply supported on both sides and a platform was made to place a load in the center with a dial indicator under the center of the truss. Figure 6 shows the testing set-up.

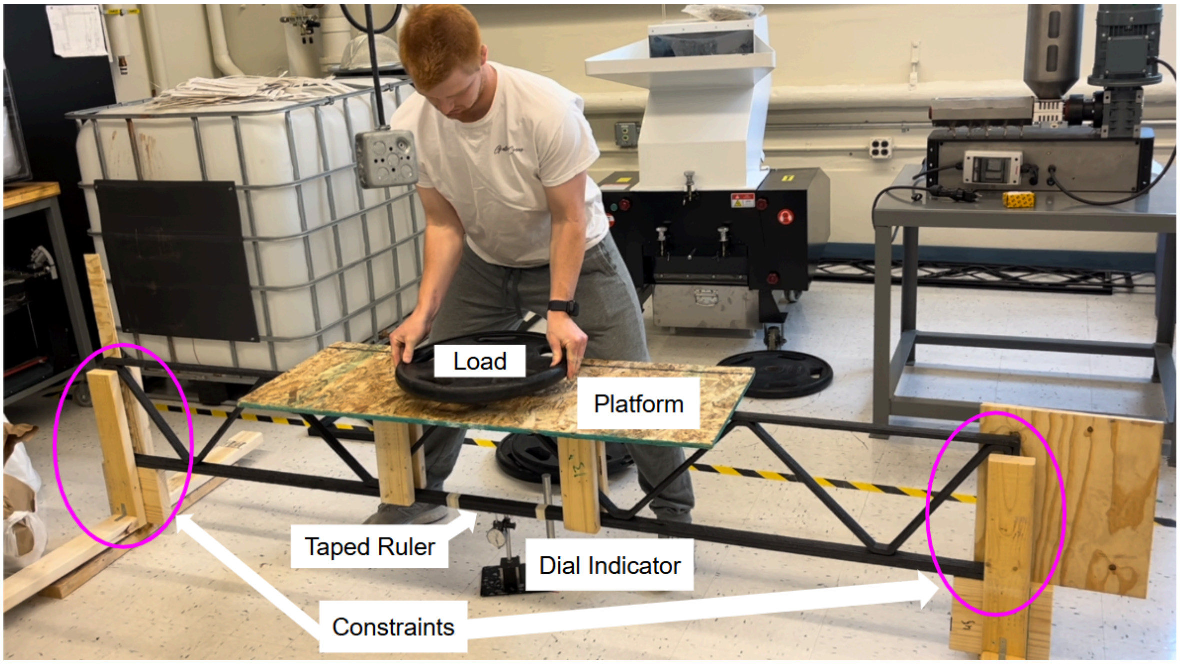

Figure 6: Single truss testing using a platform to place the load and shims to help constrain the truss.

Testing results of each truss are shown in Figure 7 with the calculated stiffness shown as a dashed line and the maximum load tested being 180 lbs.

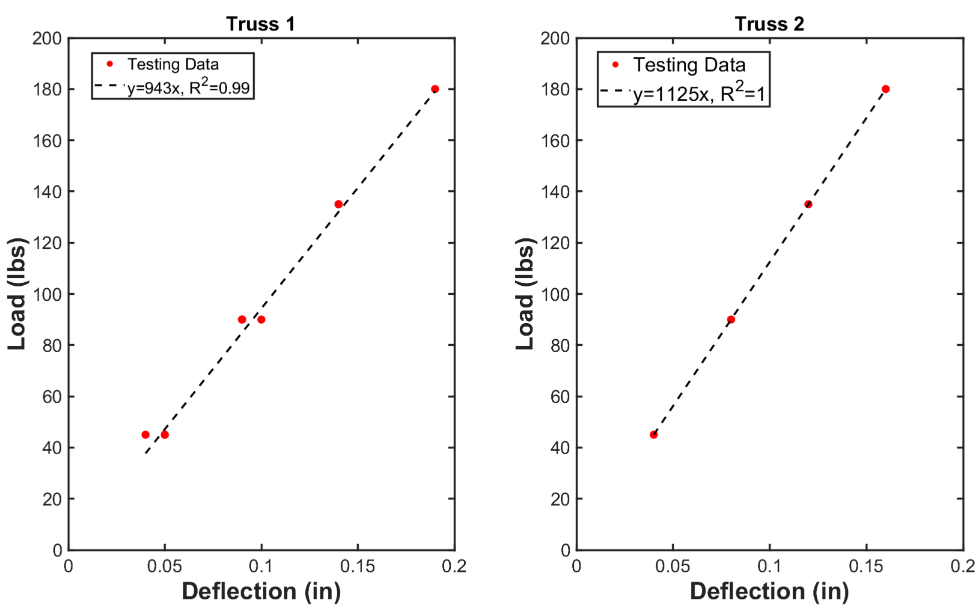

Figure 7: Load deflection plots for single truss tests.

a) Truss #1 - Lower loads were applied and released twice.
b) Truss #2 - Monotonic load application.

The results of the single truss testing show good consistency for each load and unload cycle and clear linear behavior. Truss 1 was loaded several times to feel out placing load on the platform on top of a thin truss. The resulting stiffness was 943 lb/in whereas Truss 2 had a higher stiffness of 1125 lb/in. This was attributed to producing and testing a new product where lessons were learned from the first one produced. Accordingly, the stiffness value from Truss 2 will be used for comparison to simulation.

Simulation

Following the printing and testing of the trusses at the large scale, the simulation was refined to have better agreement with the testing results. One refinement was acknowledging that the material as printed does not have the same properties as homogeneous material. To that end, a single bead from our printer was used in a flexural stiffness test and determined a modulus of 3 GPa, which was used in all subsequent simulations. In addition, adjustments were made to the constraints and load area to better represent the actual experimental conditions. A simulation, outlined in the Truss Design and Simulation Section, was done with the same loads as the testing to compare the simulation to the testing data.

Simulation and Testing Comparison

The error between the simulation and the testing was calculated as:

$$Error = \frac{Testing - Simulation}{Testing} \tag{1}$$

Table 7 shows the comparison between the testing and simulation with the testing data taken from Truss 2 and the error calculated from equation 1.

Force (lbs)	Simulation Deflection (in)	Testing Deflection (in)	Error (%)
45	0.035	0.039	10
90	0.071	0.077	8
135	0.106	0.116	9
180	0.145	0.158	8

Table 7: Single truss simulation and testing comparison using the bottom measurement point from the simulation.

The simulation deflection was within 10% of the experimental deflection for the second truss tested. This agreement gives confidence in the simulation, allowing it to be used for predictive purposes. It should be acknowledged that the material is anisotropic and that is not taken into account in the simulation.

Simulation and Testing of a Model Floor

A more realistic test of the trusses can be performed by using them in a floor structure. Accordingly, a 4 ft x 8 ft floor system was designed using 4 trusses on 16 in centers and a plywood floor surface. Three different types of structures were additively manufactured: the floor joists (trusses), end caps (girders) and pile footings. The joists and end caps are each 1 in thick and were produced by the MITHAUS group using the Cincinnati BAAM 603. The pile footings, described in Perez et al. [4] were produced by Additive Engineering Solutions[1] using both virgin and recycled PET-GF(GlassFiber). The last component is a 4 ft x 8 ft - 15/32 in thick plywood sheet attached to the joists with self-tapping screws. The complete floor system is shown in Figure 8.

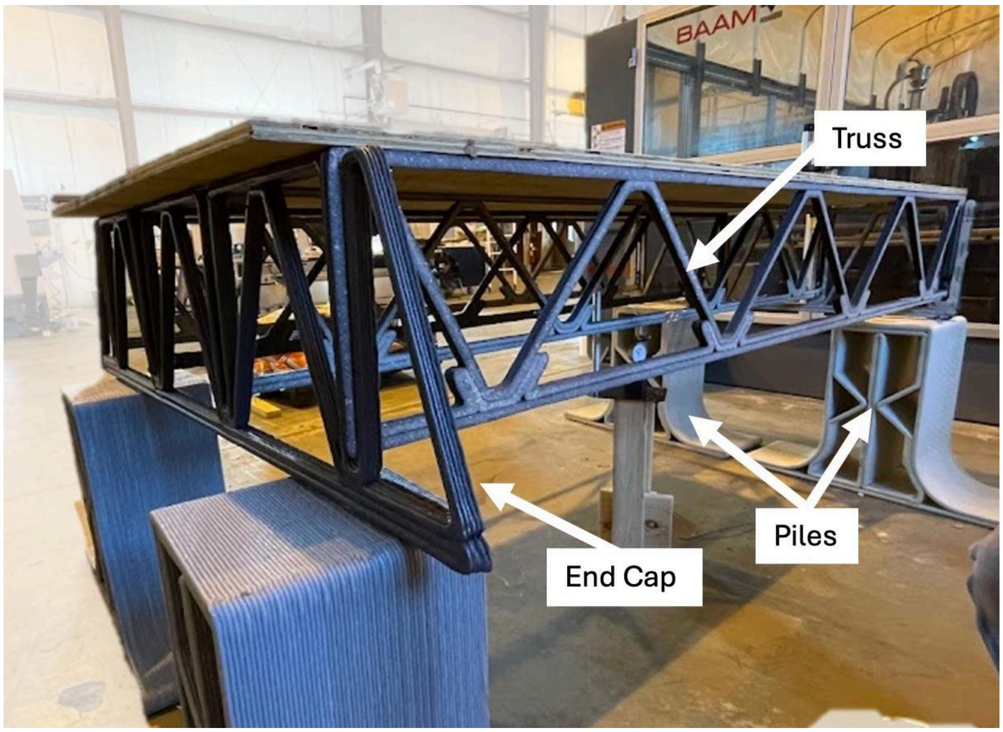

Figure 8: Floor system showing the 4 piles, two endcaps and 4 trusses on 16 in centers.

The trusses were put into the end caps with a snug fit. The plywood was fastened to the trusses with 1 ¼ in drywall screws. A pilot hole was drilled first and the plywood was rolled up-screwed from one end to the other. The plywood was not screwed into the end caps due to tolerancing stack up that left the top of the end caps short of the top of the joists. The end caps rest on the piles held by gravity.

Testing Set-Up

The load-displacement testing was conducted by loading the structure with 48 lb sand bags, 60 lb concrete bags, and 45 lb weight room plates. Displacement measurements were made at the bottom of one of the middle joists, at the middle of the joist. Figure 9 shows the experimental set-up.

[1] Additive Engineering Solutions, Akron Ohio.

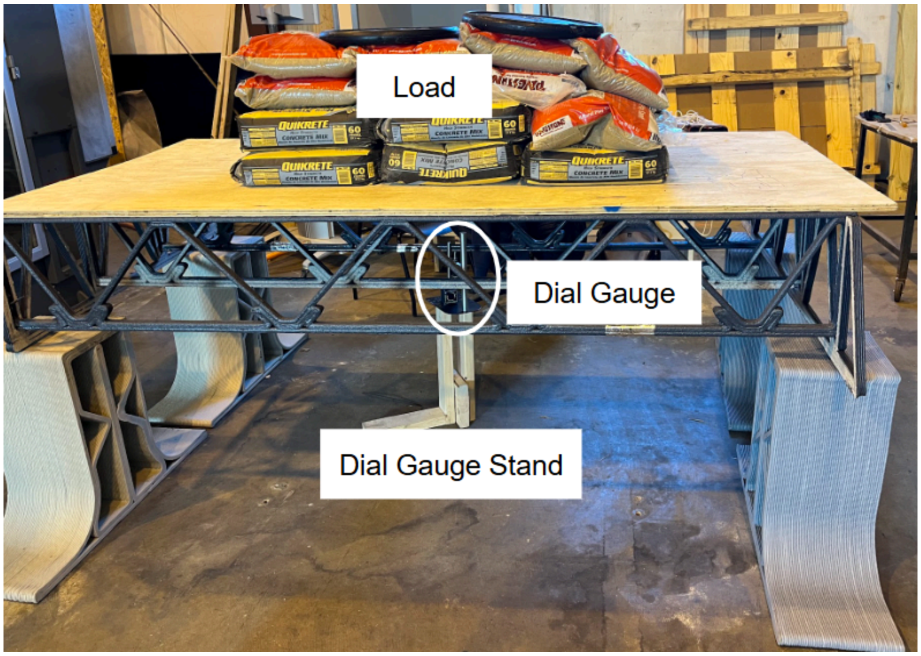

Figure 9: Experimental setup with an 1134 lbs load shown and measurements taken with a dial gauge at the bottom of a truss.

Testing occurred over 3 different days. The load was placed in the center of the structure and the testing was cyclic. Load was placed on the floor in increments, with measurements taken after each increment was placed and the load was removed at the same increments with measurements taken after each increment was removed. The dial gauge was zeroed before the start of each day of testing. The first day of testing was 11/15/2024, where the max load was 384 lbs and load was placed in increments of 48 lbs and bags with 5 cycles completed. On day two of testing, 11/25/2024, the max load with a measurement was 1134 lbs, with loads of 330, 660, 852, and 1044 lbs also tested and measured using the concrete bags and sand bags with one cycle completed. Day two of testing was 1/21/2025, the max load was 1074 lbs with loads of 360, 600, 792, and 984 lbs tested which are different from day 2 due to a broken concrete bag and 3 cycles were completed. The bags were manually loaded onto the structure, then put into the middle. Loading of the structure would cause vibration and sudden impact to the structure.

Testing Results

The results from the floor testing are shown in Figure 10.

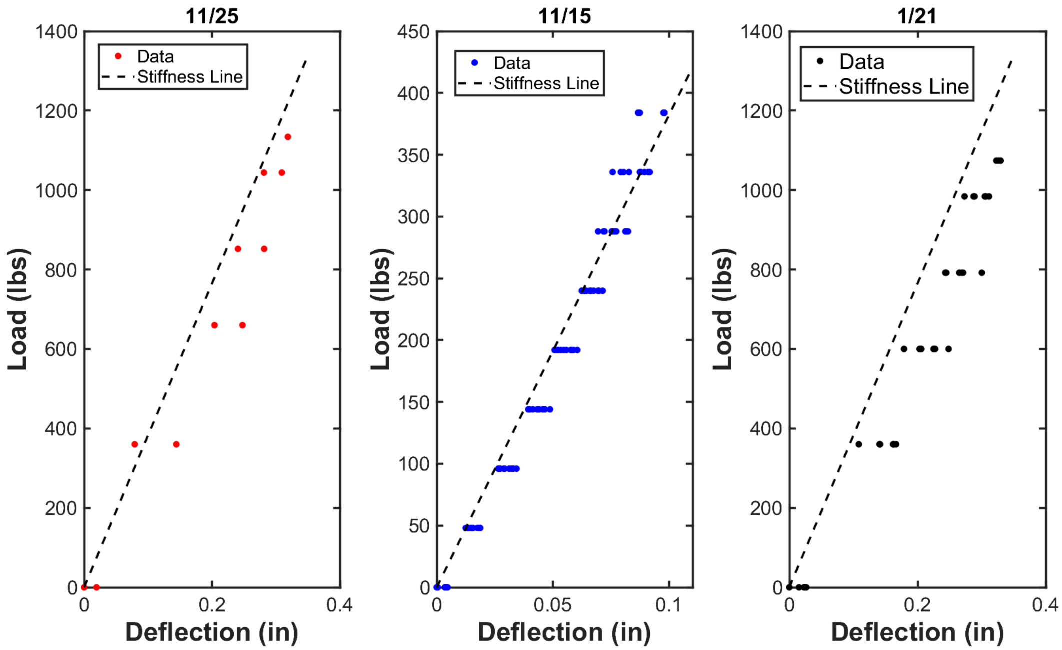

Figure 10: Testing data by testing date.

The testing data separated into the day that testing was done. On each testing day, the points shifted to the right as testing went on, due to some settling of the trusses into the endcaps, especially at higher loads. The stiffness of each cycle was roughly the same, with the dashed black line shown being the average stiffness across all cycles over all testing days; the stiffness is 3,835 lb/in.

The stiffness can be calculated as the whole data set (all days), by day, or by testing cycle. Calculating stiffness by testing cycle eliminates the error from offsets that were seen during testing. The average stiffness of the cycles was 3,835 lb/in with a standard deviation of 0.35 lb/in.

Simulation

Simulations were again performed using Fusion360 using the same material from the single truss simulation for the printed parts and plywood modeled as a material with a Young's Modulus of 6.5 GPa from matweb [24]. The floor was simulated with the endcaps constrained at the corners and a 0.05 in cut of a rectangular shape the size of the testing load where a point load is placed on the bottom of the cut. Figure 11 shows the simulation set up.

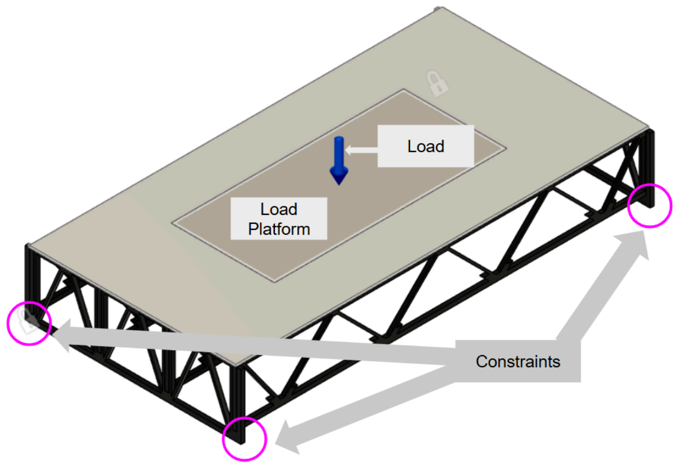

Figure 11: Floor simulation with the printed parts modeled with the same material as in the simulation in Figure 2 and constrained as pin joints at the corner of the end caps.

The load-displacement data from the simulation remained over the range of 0-400 lbs, and yielded an overall stiffness of 4,009 lb/in.

Simulation and Experiment Comparison

Figure 12 plots the simulation and the experimental data for loads up to 384 lbs, which is only slightly larger than the HUD live load standard of 300 lbs [9].

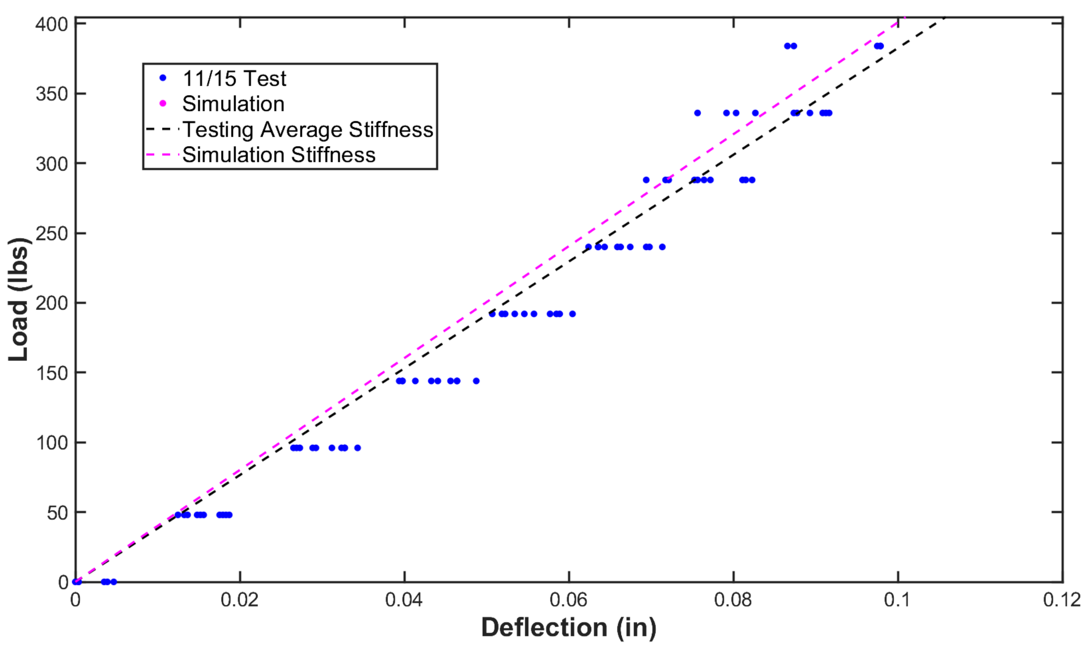

Figure 12: Simulation and testing comparison for HUD loads with the simulation stiffness shown as the pink line and the average testing stiffness as the black line.

With the removal of the load after each cycle there is a drift to the right since the floor system does not return to zero deflection. This behavior is attributed to settling of the structure (trusses into end caps) occurring as the load is applied and removed, as well some potential shear deflection of the plywood. Creep could also contribute, and long term tests are currently underway to quantify this effect.

Testing at Higher Loads

A series of experiments over several days to measure the floor deflection with loads well above the HUD limit of 300 lb were conducted. Loads up to 1,200 lb were applied, again with successive loading and unloading. While shifts to the right (deflection offsets) were again observed between tests, the within test stiffness remained consistent with that of the simulation and low load tests. Finally, an ultimate load test was performed, adding weight until a clear structural failure occurred. The floor system finally failed at 4,480 lbs when two truss chords buckled and fractured.

Maximum k/w Truss Design

With confidence in the single truss simulation, it is possible to explore the design space to find the truss with the maximum stiffness to weight (k/w) ratio. Using the same truss design (design 2 with 5 nodes) and keeping the length the same (8 ft), the height of the truss can be easily varied both in design and in manufacture. The height of the prototypes used here is 13 in. Using the Fusion360 simulation conditions discussed above, the height was varied to 10, 15, 17, and 19 in. Figure 13 shows the results of the simulations, and using a quadratic curve fit to the data, the maximum value of k/w was at truss height of 16.3 in.

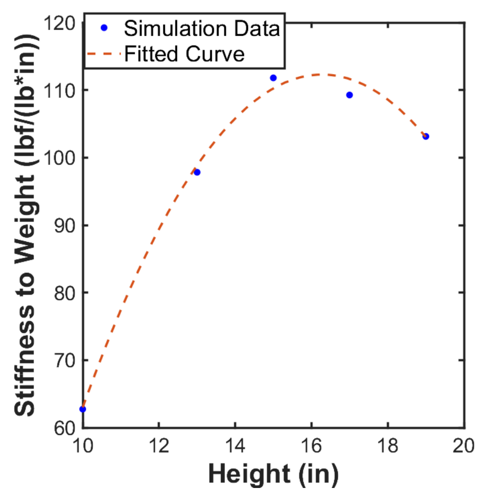

Figure 13: Truss height optimization with stiffness to weight ratios were calculated and plotted, with a quadratic curve (R^2= 0.99) fitted to the data.

Conclusions

The objective of this work was to demonstrate LSAM produced components made of recycled polymer composites can be produced and implemented into a floor system. To that end a lightweight truss design was explored to serve as structural support for floor or roof components in a typical small home. Using LSAM and an rPET-GF 30 material, a truss weighing 13 lbs was produced in 13 minutes and achieved a central load/deflection stiffness of

1,125 lb/in. Single truss simulation was accurate within 10% and can be used for design optimization. The floor system was constructed using 4 such trusses with a plywood floor panel and was shown to be well within HUD standards for deflection under typical load of 300 lbs. The floor has also withstood loads exceeding 4,000 lbs without failure. The floor ultimately failed at 4,480 lbs.

There are improvements to be made. The as-built truss cost is still high owing to the use of expensive material and modest production rates. The former can be reduced by creating a material stream from a tailored recycling process that is attuned to the needs of these structures, while the latter can be addressed by using high capacity LSAM equipment. For example, while the BAAM has a maximum throughput of 80 lb/hr, the Thermwood 1540 has a rate of 500 lb//hr. Using commodity prices for rPET and short glass fiber can decrease material cost by 3-5 times. Since cost is directly related to material cost and machine time, this could lead to a cost reduction to a few dollars for this typical truss. Costs for larger trusses would scale accordingly. In addition, there is structural optimization work that can further improve the structure. This work combined with work being done on tool path modifications has the potential to unlock a much larger design space than the one that was explored in this work.

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